Q-switched Erbium Doped Fiber Laser Incorporating Zinc Oxide in Polyvinyl Alcohol as Passive Saturable Absorber

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***Abstract*— The search for the ideal saturable absorber in realizing a better pulsed laser is still on-going. With a wider bandgap, zinc oxide promises better laser performance in terms of higher stability, better temperature durability, and higher power operation. These properties were clearly demonstrated using a Q-switched Erbium-doped fiber laser residing a newly fabricated Zinc Oxide embedded in polyvinyl alcohol (ZnO-PVA) based film as a passive saturable absorber in a ring laser cavity. The surface morphology of the fabricated ZnO-PVA film shows a thoroughly mixed composite with a measured film thickness of 22 µm. The Q-switched laser operates at 1557.6 nm within a tunable input pump power from 23.8 mW to 134.8 mW. At maximum input pump power, the generated pulse produce shortest pulse width, maximum repetition rate, maximum instantaneous peak power maximum pulse energy of 4.52 µs, 71.84 kHz, 6.7 mW and 31.6 nJ, respectively. The first beat note of the measured signal to ratio is around 61 dB, which indicates the stability of the generated pulse. The proposed Q-switched laser can be further improved and can find potential application in metrology, fiber sensor, medical diagnostics and the most commonly known optical communication.**

***Index Terms*— Q-switched; Saturable Absorber.**

I. INTRODUCTION

Pulsed laser generation can be achieved either through mode-locking or Q-switching techniques. Q-switching approach is taken in the study where the typical repetition rates are in kHz and the pulse width ranges from microsecond to nanosecond [1]. Chen et al. [2] describe Q-switching regime as the result of high energy content in a gain medium over a short period of time. Q-switching and mode-locking alike, a device is needed to modulate the intracavity losses. This helps in the formation of pulses. Active and passive [3,4] means of Q-switching can be utilized with the latter being more preferred for its simplicity, compactness, and cost-effectiveness [5] . The main application of pulsed laser in Q-switched regime is in such in machining and materials processing [6]. Q-switched fibre lasers have been demonstrated using a carbon nanotubes [7], graphene [8], Topological Insulator (TI), Transition Metal Dichalcogenide (TMD), Black Phosphorus (BP) [9] and most recently, Zinc Oxide [10-13].

Zinc Oxide (ZnO) is an II-IV compound semiconductor, whose covalence is on the borderline between ionic and covalent semiconductors used for many applications especially for electronics, optoelectronics and sensor. Generally, ZnO is a hexagonal wurtzite structure (Figure 1) exhibiting partial polar each zinc atom is surrounded by four oxygen atoms, which are located at the corners of a nearly regular tetrahedron. The structure has alternating planes implicated of tetrahedral coordinated Zn^{2+} and O^{2-} ions attached along c-axis, where the ends are terminated with either polar and non-polar surfaces. ZnO is a valuable material for the optoelectronics devices due to its wide bandgap of 3.37 eV at room temperature and high excitation binding energy of 60 meV enables to be used for light emitting diodes [14], photodetectors [15] and laser diodes [16]. Advantages associated with wider bandgap includes higher breakdown voltages, lower noise generation, ability to sustain large electric fields, high power operation and high temperature properties [17].

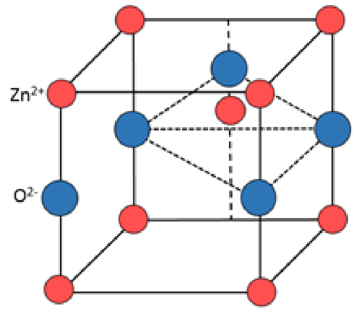


Figure 1: Wurtzite structure of ZnO

Ahmad et al [10-13] used Zinc Oxide powder with particle size around 20-50 nm, and then is mixed with silane and ethanol to form Zinc Oxide film based passive saturable absorber with the thickness of 0.15 ± 0.01 mm. The optical properties of the developed ZnO film have saturation intensity of 0.016 MW/cm^2, the modulation depth of 3.5% and a broadband absorption from 1000 nm to 1600 nm, making it a good candidate to be applied as a passive saturable absorber. They reported a Q-switched and tunable wavelength Q-switched at 1.5 micron region. Apart from that, they also reported a Q-switched Ytterbium doped fiber laser at 1 micron region using the same fabrication method of Zinc Oxide film based passive saturable absorber. For Q-switched Erbium-doped fiber laser (EDFL), they reported the pulse generated operates at 1561 nm, range of tunable repetition rate from 41.7-77.2 kHz, the shortest pulse width of 6 µs and signal to noise ratio of 56 dB. Meanwhile, Aziz et al [13] synthesis Zinc Oxide powder by mixing Zinc Nitrate and Hexamethylenetetramine in de-ionized (DI) water. After that, they develop Zinc Oxide based passive saturable absorber by mixed the synthesized Zinc oxide power in polyvinyl alcohol (PVA). The develop ZnO-PVA film based saturable absorber is around 50 μm with the performance of the generated pulse operates at 1560.4 nm, range of tunable repetition rate from 11.8 -77.9 kHz, the shortest pulse width of 7 μs and signal to noise ratio of 62 dB. The approach of Ahmad et al [10-12] is promising, but the developed film is quite thick, which the most reported film is around 50 μm or less [18]. Meanwhile, Aziz et al [13] are not reporting the characterization of the synthesized Zinc Oxide powder to be used as main materials. In this work, we reported zinc oxide based passive saturable absorber by using commercially available zinc oxide powder as starting material and polyvinyl alcohol (PVA) as a binder to develop Zinc Oxide- polyvinyl alcohol (ZnO-PVA) based passive saturable absorber. The characterization and the performance of the developed film as a passive saturable absorber is reported throughout the manuscript.

II. Material preparation

In this experiment, polyvinyl alcohol (PVA) was selected as a host polymer due to excellence film forming and high flexibility. The PVA was fabricated by adding 1 g of PVA powder (Sigma Aldrich, 40000 Mw) into 120 ml of de-ionized (DI) water with the aid of magnetic stirring at a temperature of 145 °C for 5 hours. The resultant of the process is dissolved PVA suspension which used as a binder. The Zinc Oxide (ZnO) based passive saturable absorber fabricated by adding 25 mg of ZnO powder (Alfa Aesar, 99.99 % trace metal basis, 81.37 Mw) with 5 ml of the dissolved PVA suspension. First, the ZnO-PVA mixture is then sonicated for two hours and then undergoes centrifuges at 5000 rpm for 5 minutes. After the centrifuges, the ZnO-PVA solution was decanted into a petri dish and kept in a dry cabinet at ambient temperature for two days to develop ZnO-PVA film based passive saturable absorber. The surface morphology of the developed film then was investigated using low vacuum scanning electron microscope (LV-SEM) (JEOL, JSM-IT300) as shown in Figure 2. The captured image showed a thoroughly mixed of Zinc oxide powder in PVA host polymer. The thickness of the developed film was measured using 3D measuring laser microscope (Olympus, LEXT OLS4100), as shown in Figure 3. The film was attached on the double sided tape to fix the film position for precise measurement. The thickness was measured by taking the distance between the wrinkles surfaces (double sided tape) and the smooth surface which is the ZnO-PVA film. The height indicated in the figure depicted the thickness, which is recorded as 22 μm. To use the ZnO-PVA film as a passive saturable absorber, a small portion of the developed ZnO-PVA film around 1 mm^2 x 1 mm^2 was attached to the end of fiber ferrule, and then integrated into the laser cavity assisted by fiber connector.

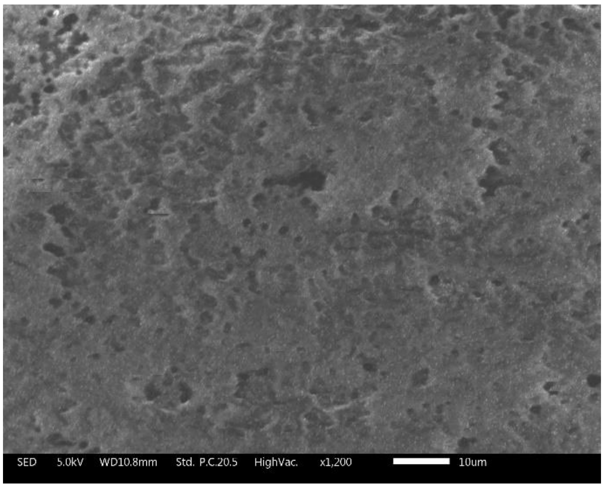


Figure 2: Scanning electron microscope image of developed ZnO-PVA film

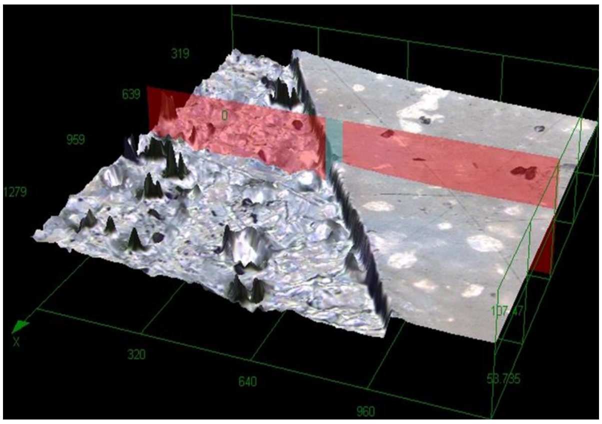


Figure 3: Thickness measurement of ZnO-PVA film

III. Experimental Set-up

Experimental setup of the Q-switched Erbium-doped fiber laser (EDFL) in a ring cavity with ZnO-PVA polymer composite as a passive saturable absorber is depicted in Figure 4. The performance of the laser cavity is solely depending on the process of increasing the pump power and the characteristics of the ZnO-PVA based passive Saturable absorber.

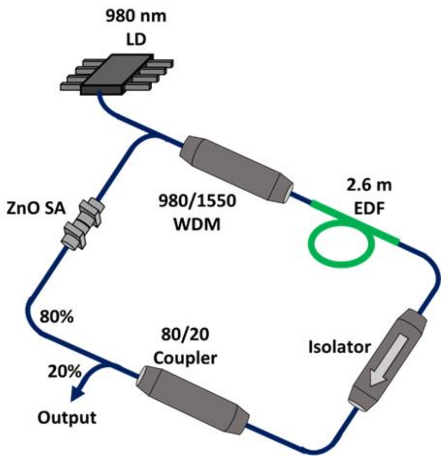


Figure 4: Laser cavity configuration setup

The cavity consists of a 2.6 m long Erbium doped fiber (EDF), a 980/1550 nm wavelength division multiplexer (WDM), an isolator, 80/20 output coupler and a newly developed ZnO-PVA based passive saturable absorber in a ring configuration. The EDF used has core and cladding diameters of 8 µm and 125 µm respectively, a numerical aperture of 0.16 and Erbium ion absorptions of 45 dB/m and 80 dB/m at 1480 nm and 1530 nm, respectively. It is pumped by a 980 nm laser diode via the WDM. An isolator is incorporated in the laser cavity to ensure unidirectional propagation of the oscillating laser. The output of the laser is tapped from the cavity through an 80/20 coupler. 80% of the light is fed back into the cavity while the other 20% is characterized as laser output. The optical spectrum analyzer (OSA) is used to inspect the spectrum of the EDFL with a spectral resolution of 0.05 nm whereas the oscilloscope is used to observe the output pulse train via a 460 kHz bandwidth photo-detector. A radio frequency spectrum analyser (RFSA) is used to measure the signal-to-noise (SNR) of the generated pulsed and the optical power meter (OPM) measures the average output power.

IV. Experimental Result

The input pump power is gradually increased to obtain the lasing threshold for Q-switching operation. Self-started Q-switching pulse is observed as the input pump power reaches 23.9 mW. The stable pulse train is obtained throughout the varying input pump power of 23.9 mW to 134.8 mW. Beyond that, the Q-switched pulse started to become unstable and eventually diminished. The range of tunable input pump power is wider than many of the works based on other SAs such as carbon nanotubes (CNTs), graphene, and black phosphorus (BP) [19-22]. At maximum input pump power, the Q-switched pulse is centered at a wavelength of approximately 1557.6 nm with an average optical power of -21.9 dBm as shown in Figure 5.

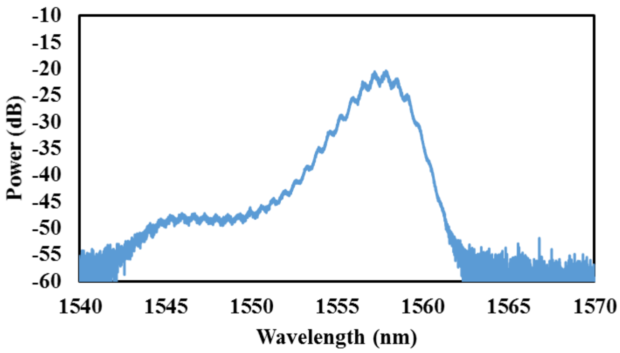


Figure 5: Optical spectrum at a maximum pump power of 134.8 mW

Figure 6(a) shows the pulse train of 71.84 kHz obtained at maximum input pump power with no observable amplitude modulations, indicating that the self-mode locking (SML) effect is fully suppressed during the Q-switching operation. Figure 6(b) shows the adjacent pulse separation of 13.7 µs and the corresponding single pulse envelope with the shortest pulse width of 4.5 µs is illustrated in Figure 6(c).

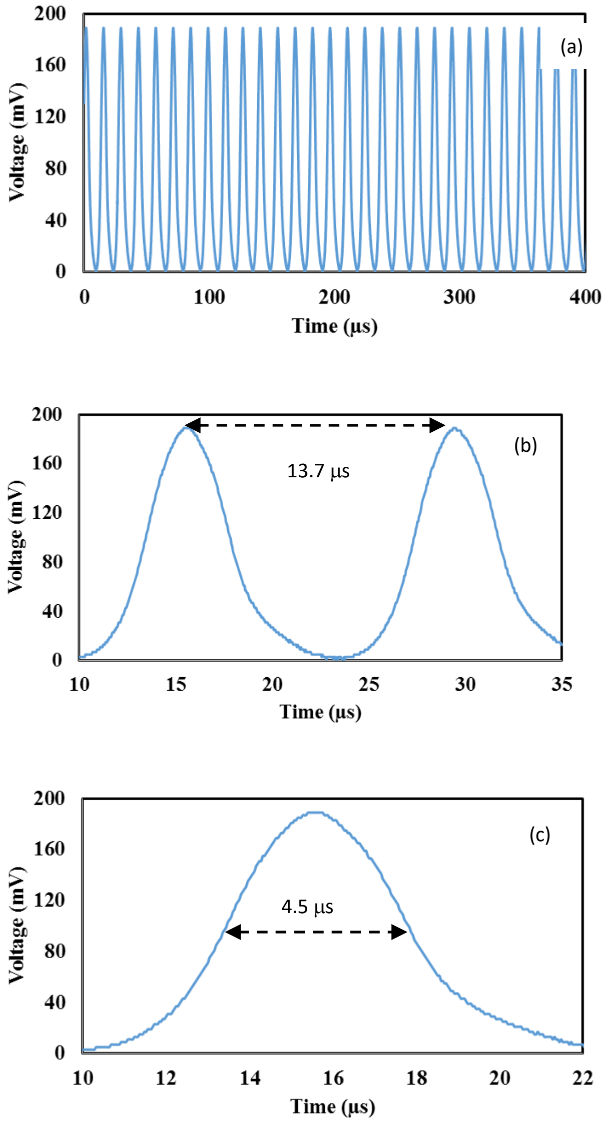
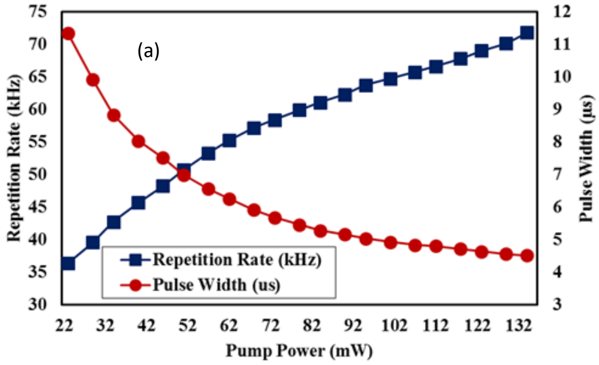


Figure 6. Oscilloscope trace at maximum pump power of 134.8 mW (a) pulse train (b) pulse separation and (c) single pulse envelope

Figure 7 shows the typical trend of a Q-switched pulse [23]. As the input pump power is varied from threshold to the maximum, the repetition rate increases almost linearly from 36.34 kHz to 71.84 kHz, while the pulse width reduces from 11.36 µs to 4.52 µs, as shown in Figure 7(a). This is caused by the shorter time for the inversion number of the gain medium to reach the threshold due to the increasing pump power. When compared to previously reported works on ZnO based saturable absorber, the maximum repetition rates of 71.84 kHz is fairly comparable if not higher than others [10-13]. Figure 7(b) shows the consistent increment of the peak power and pulse energy with the increasing pump power yielding a maximum of 6.57 mW and 31.6 nJ, respectively. The pulse energy obtained is fairly higher than other reported Q-switched laser based on multi-walled carbon nanotubes (MWCNTs), a topological insulator (TI), and graphene [24-26].



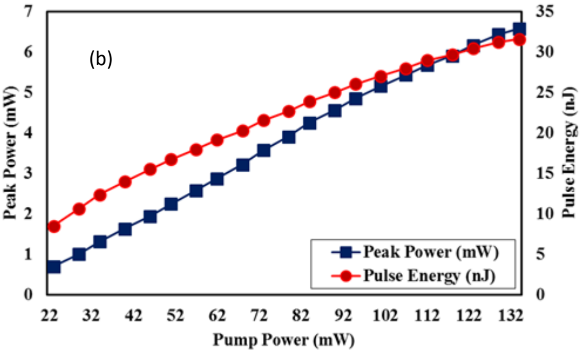


Figure 7. (a) Repetition rate and pulse width (b) peak power and pulse energy in a function of pump power.

The output spectrum of an RFSA indicating a signal to noise ratio (SNR) of about 61 dB at the fundamental frequency of 71.8 kHz is shown in Figure 8. The high SNR value depicted the high stability of the Q-switching operation with up to 13th order harmonics of fundamental repetition rate is observed within a 1000 kHz span. The high stability of the laser exceeded many reported works as such by Ahmad et al. using ZnO based SA [10-12], Popa et al. using graphene SA [8], as well as Sun et al. [27] using Bismuth Selenide (Bi_2Se_3) based saturable absorber.

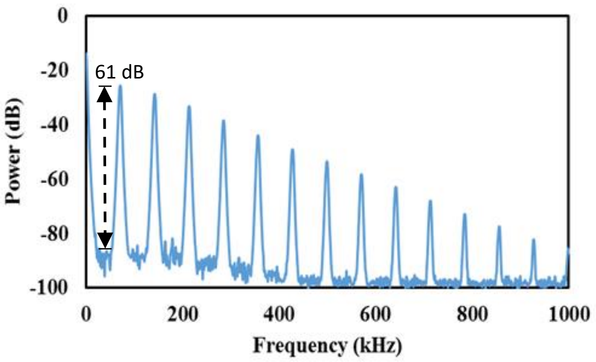


Figure 8. Signal to noise ratio at a repetition rate of 71.8 kHz.

V. Conclusion

Q-switched Erbium-doped fiber laser (EDFL) was successfully demonstrated by utilizing Zinc Oxide embedded in polyvinyl alcohol (PVA) as a passive saturable absorber. The performance of the generated pulse was illustrated, tabulated and discussed throughout the manuscript. The finding could find an interest to explore Zinc oxide nanostructure such as nanowires and nanorods to be applied as a passive saturable absorber.

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